Looking for the Quark-Gluon Plasma with Charm Quarks

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The Fundamental Particles

- All “matter” made up of fermions
- Forces “mediated” by bosons
- All “normal” matter made of up, down quarks and electrons

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2,...

Leptons spin = 1/2		
Flavor	**Mass GeV/c^2**	**Electric charge**
ν_e electron neutrino	$< 7 \times 10^{-9}$	0
e electron	0.000511	–1
ν_μ muon neutrino	< 0.0003	0
μ muon	0.106	–1
ν_τ tau neutrino	< 0.03	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	**Approx. Mass GeV/c^2**	**Electric charge**
u up	0.005	2/3
d down	0.01	–1/3
c charm	1.5	2/3
s strange	0.2	–1/3
t top (initial evidence)	170	2/3
b bottom	4.7	–1/3

BOSONS

force carriers
spin = 0, 1, 2,...

Unified Electroweak spin = 1	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.22	–1
W^+	80.22	+1
Z^0	91.187	0

Strong or color spin = 1	Mass GeV/c^2	Electric charge
g gluon	0	0

Quarks and Gluons

Quarks		Anti-quarks	
u	up	u	anti-up
d	down	d	anti-down
s	strange	s	anti-strange
c	charm	c	anti-charm
b	bottom	b	anti-bottom
t	top	t	anti-top

Carry 'Color' Charge

red blue green   red blue green

Bound together by exchanging gluons

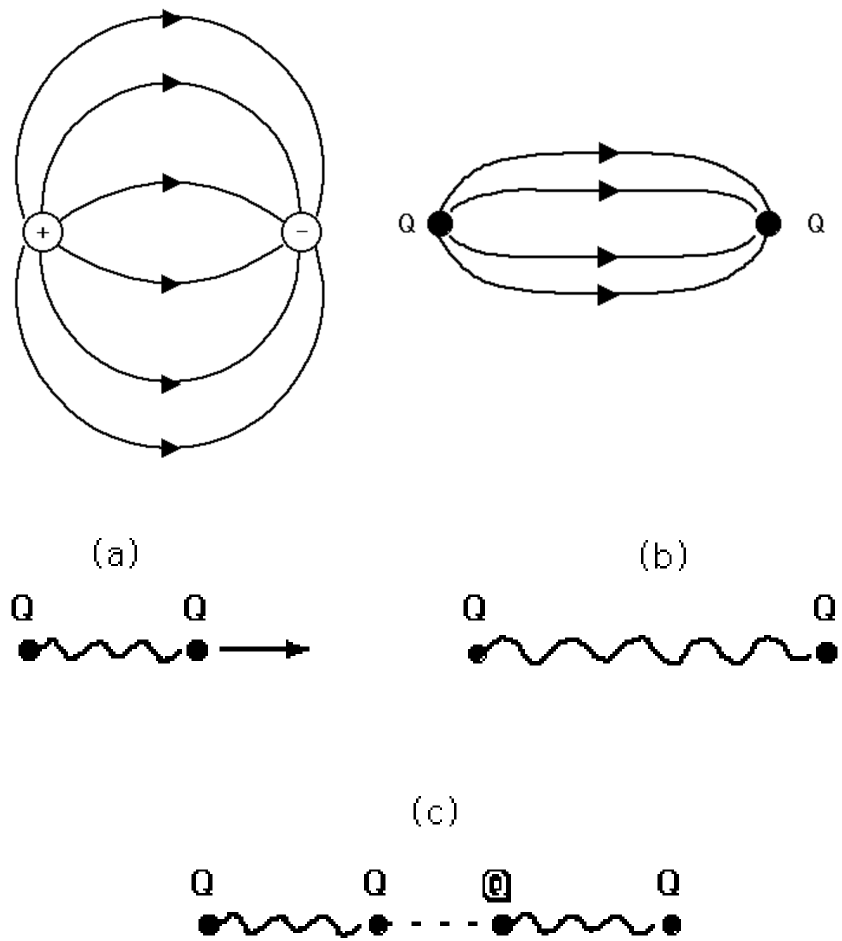
- Quarks and Gluons interact via the strong nuclear force
- Quarks carry color charge, antiquarks carry anticolor
- Gluons carry color AND anticolor
- Unlike photons, gluons interact with each other as well as with quarks (Non-abelian Guage Theory)

The Strong Interaction

- Potential given by

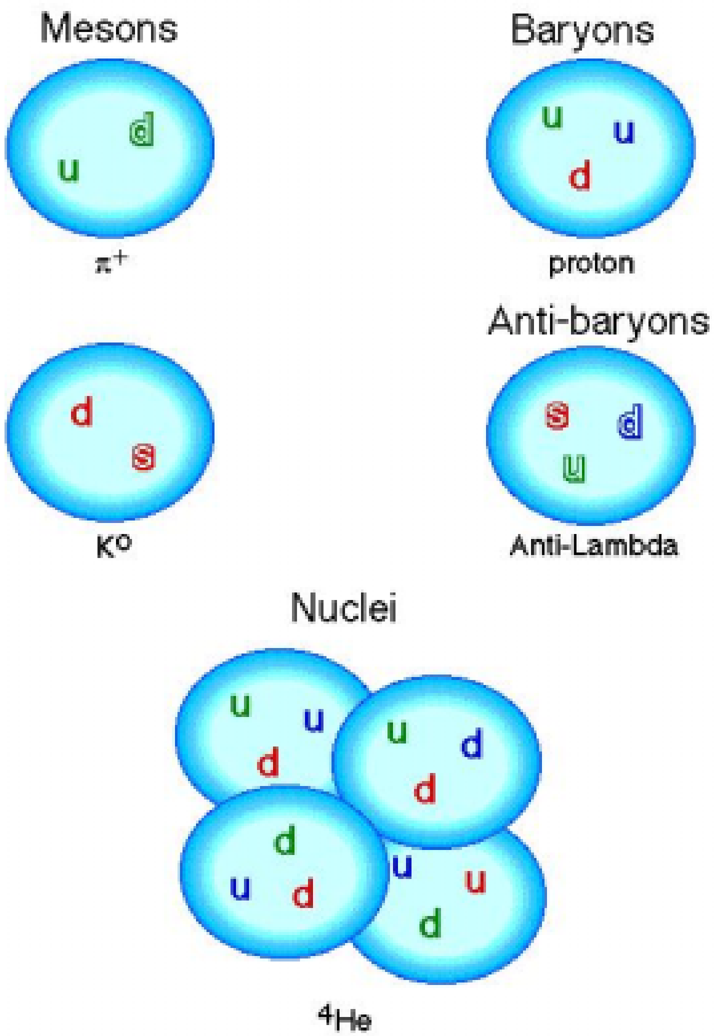
$$V(r) = \frac{4}{3}\frac{\alpha_s}{r} + kr$$

- For small r, analogous to electromagnetic interaction
- For large r, increasing potential --> confinement
- Only "color neutral" states are allowed

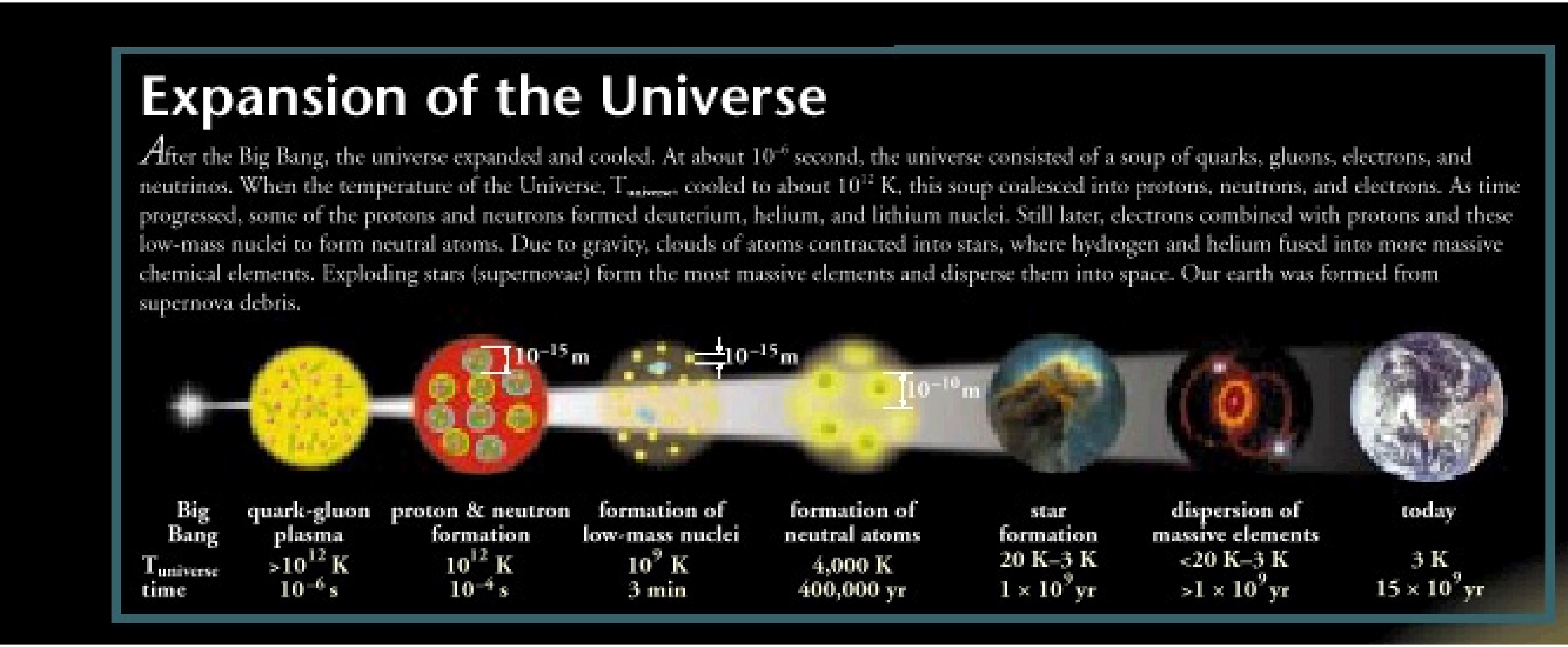


Hadrons--"Bags" of Matter

- Mesons are made up of one quark and one antiquark
- Baryons are made up of three quarks, antibaryons of three antiquarks
- Other "color neutral" states are theoretically possible, but have not been observed
- Quarks in nuclei are still bound within their neutron or proton



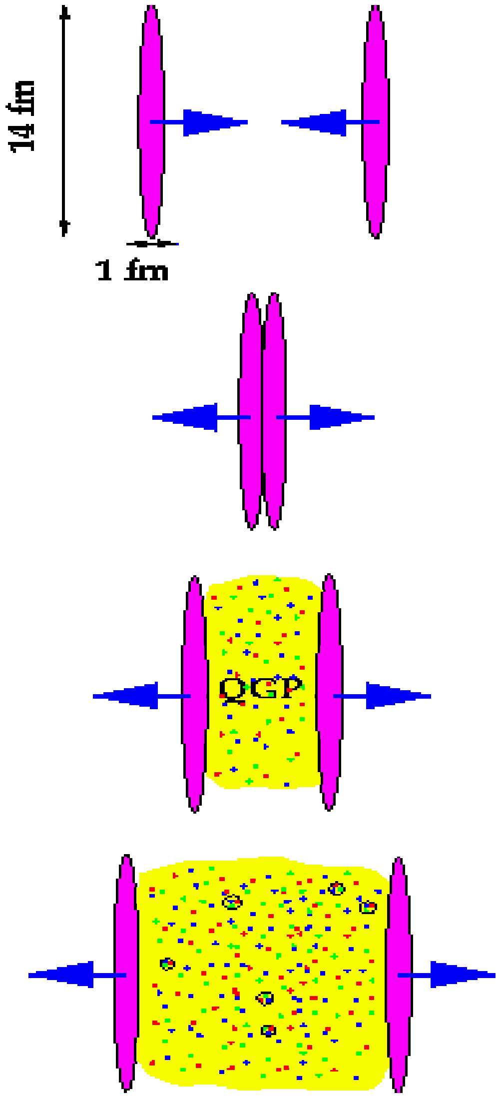
Nuclear Matter under Extreme Conditions



- Under extreme temperature and/or density, quarks and gluons are thought to be deconfined
- Universe consisted of a deconfined state--the Quark-Gluon Plasma until microseconds after the Big Bang

The “Little Bang”

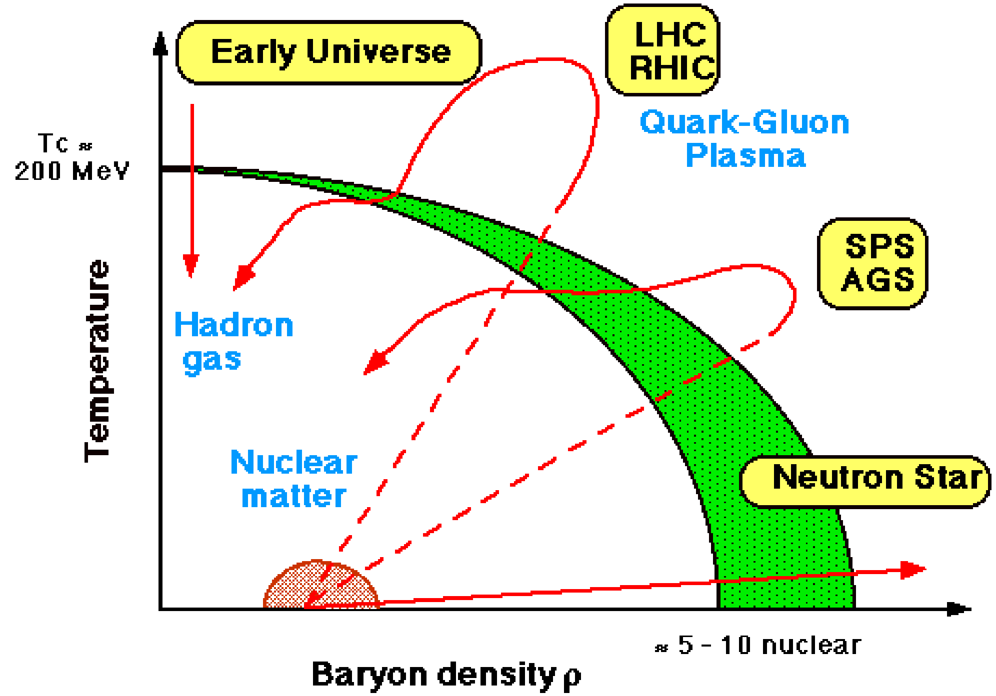
- Nuclei collide at nearly the speed of light
- Interactions deposit a large amount of energy in central region--form a QGP??
- System expands and cools, passing back through the phase transition into normal hadronic matter



Nuclear Matter Phase Diagram

- At high temperature and density, nuclear matter is expected to undergo a phase transition to a Quark-Gluon Plasma

- Recreates the state of matter in the universe a few microseconds after the Big Bang



The Phase Transition(s)

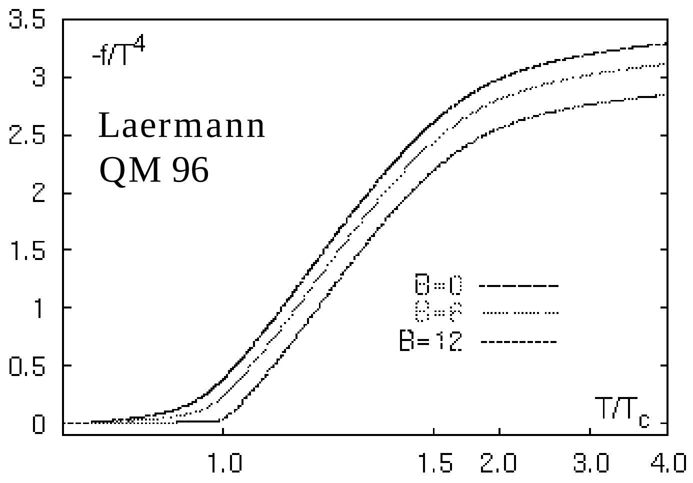
- The phase transition is actually two transitions:

  Deconfinement Transition:
  Quarks and Gluons are no longer confined to hadrons

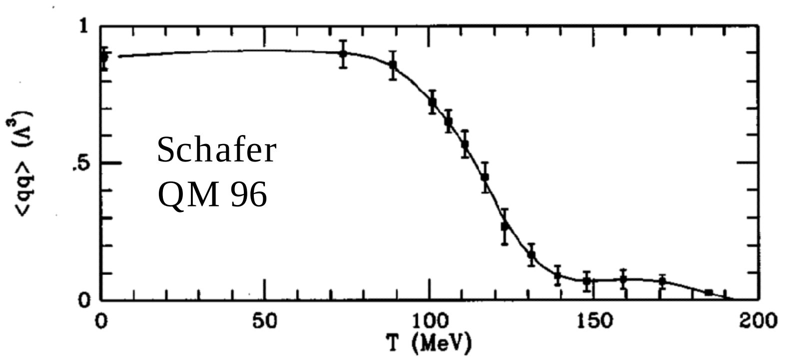
  Chiral Symmetry Restoration:
  Quark Condensate goes to ~0

- Recent Lattice Calculations suggest a transition temperature of ~150-200 MeV--should be accessible experimentally

Deconfinement Transition

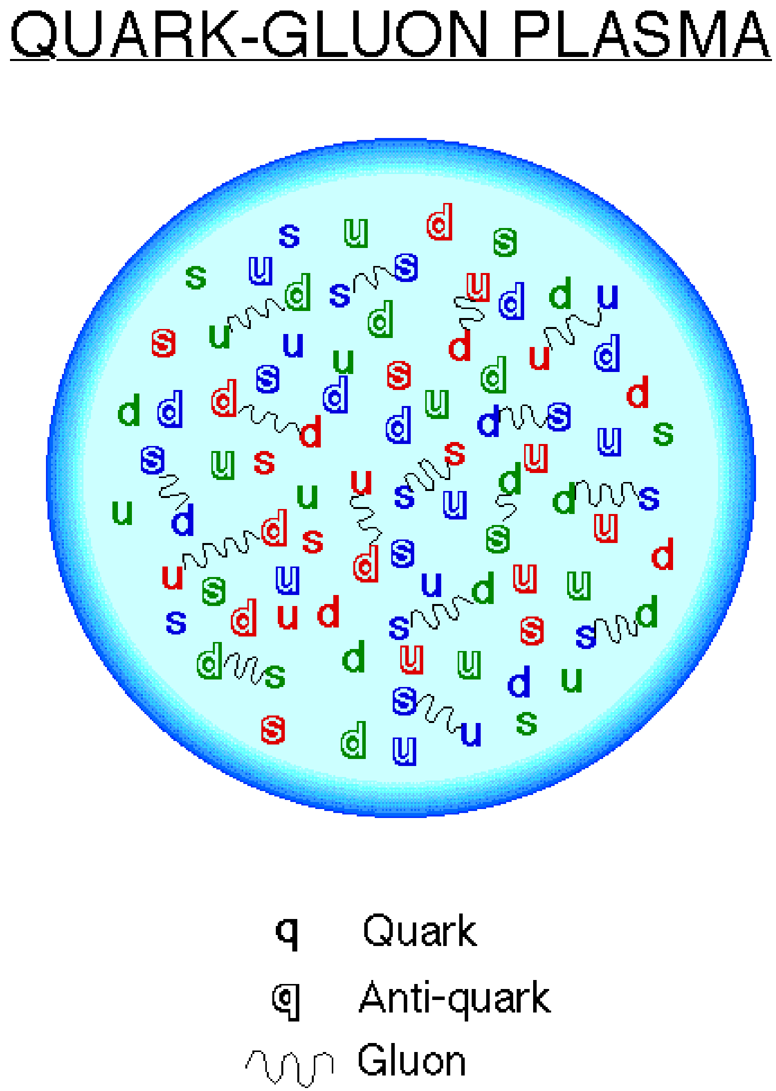


Chiral Restoration



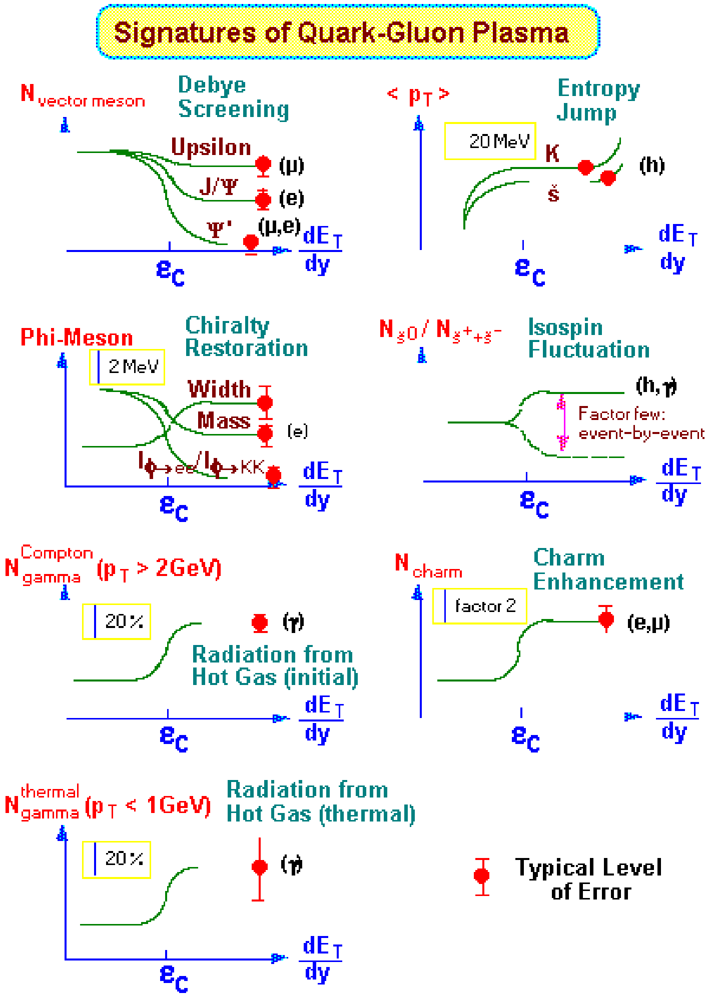
The Quark-Gluon Plasma

- Free “Gas” of Quarks and Gluons
- “Color ionized”--interacts readily with colored objects
- Increased gluon-gluon “fusion”--large antiquark content
- Lowered quark masses--large strange and charm quark content
- Increased quark-antiquark annihilation--enhanced lepton production (Drell-Yan)



Signatures of the QGP

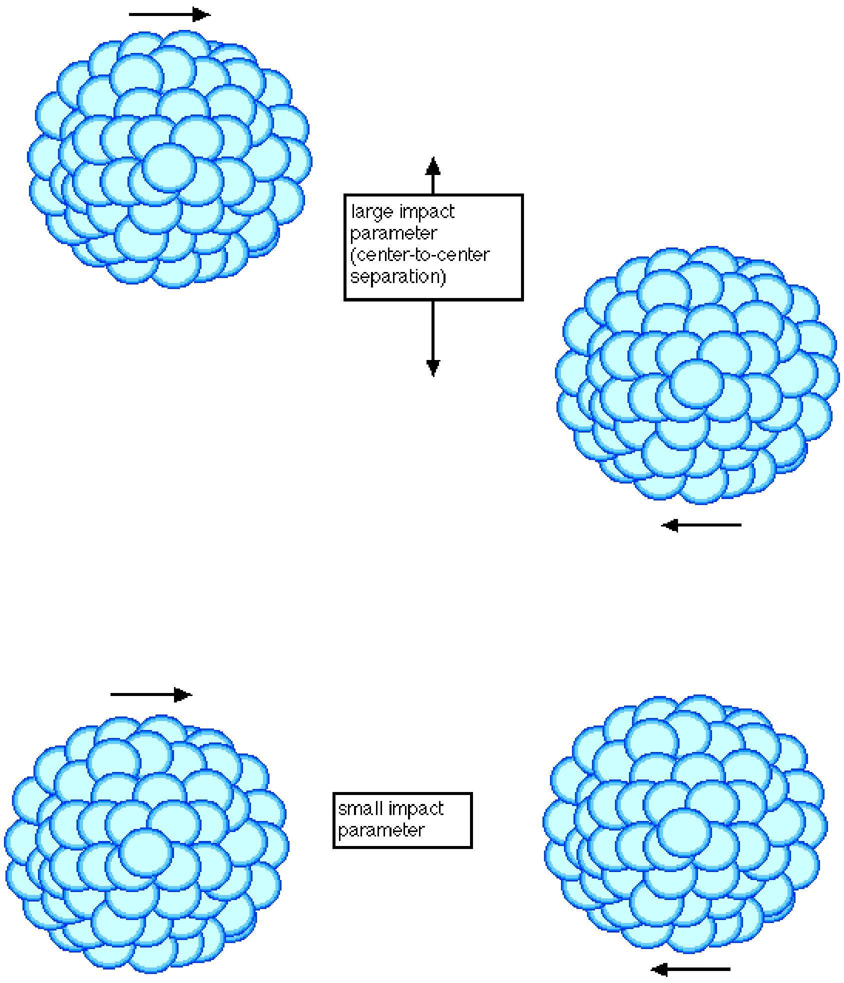
- **Deconfinement Probes:**
  - J/Ψ, Ψ' Suppression
  - Increased dE/dx of partons (Jet Quenching)
  - Strangeness, antibaryon enhancement
  - Direct photons 2-5 GeV from gluon-quark Compton scattering
  - Enhanced dilepton pairs 1-3 GeV from quark-antiquark annihilation
- **Chiral Symmetry Probes:**
  - Change in ρ, ω, ϕ mass, width and BR
  - Disoriented Chiral Condensates



S. Nagamiya, PHENIX

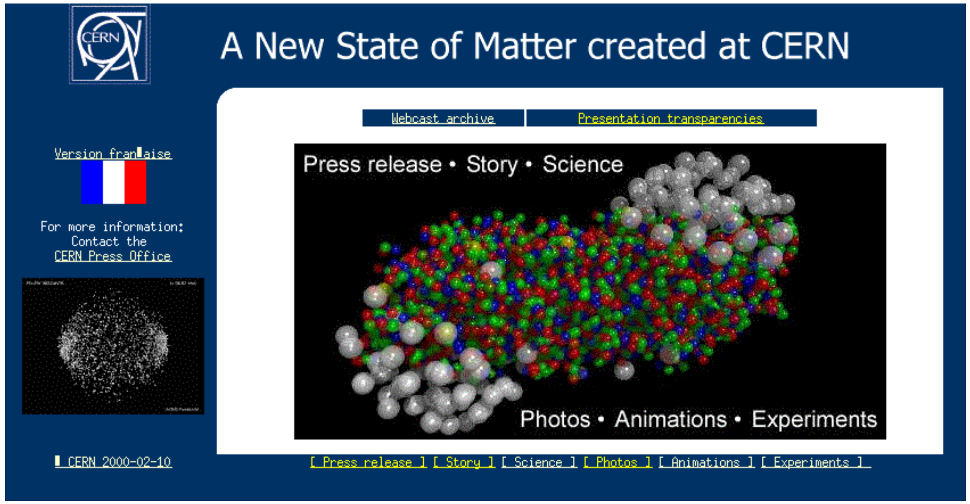
Varying the Energy Density

- Collide various systems ranging from proton-proton to Pb-Pb
- Within a system, geometry of collision (impact parameter) allows for a natural variation of energy density



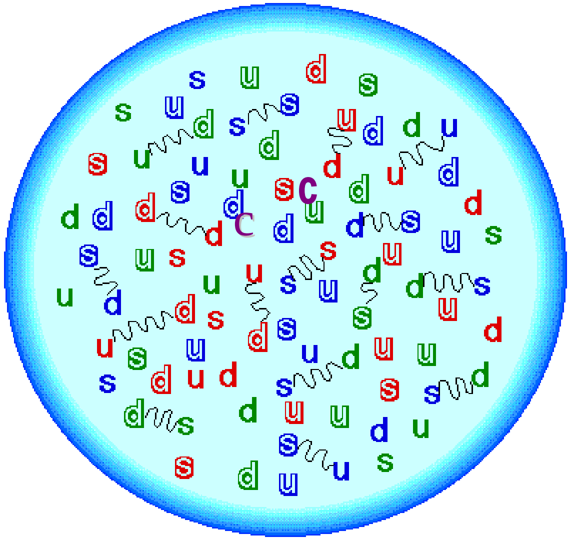
Recent CERN Announcement

Http://www.cern.ch/CERN/Announcements/2000/NewStateMatter/

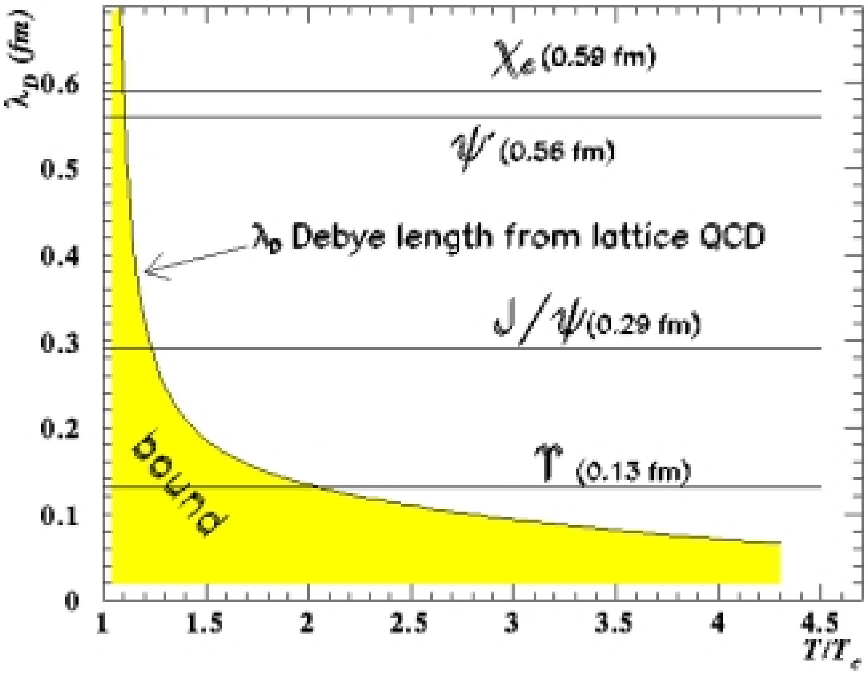


- "Circumstantial Evidence" for QGP includes:
  - » J/Ψ Suppression
  - » Enhanced Production of Strange Particles
  - » Temperature ~180 MeV from particle abundance ratios
  - » Energy density ~2-4 GeV from extrapolating back final state energy

Debye Screening



C-Cbar screened in a QGP



- J/Ψ is a bound state of charm-anticharm quarks, formed by gluon fusion
- In a deconfined medium, attraction between c and cbar is screened (Matsui and Satz)
- As Debye length decreases with increasing temperature, different states are screened

“Normal” J/Ψ Suppression

- Initial expectation was J/Ψ would not interact in normal nuclear matter
- Yield in pA data far exceeded expectations
- A dependence of pA data indicated absorption well beyond expectation
- These puzzles can be resolved by “color octet model”--explains “normal J/Ψ Suppression”

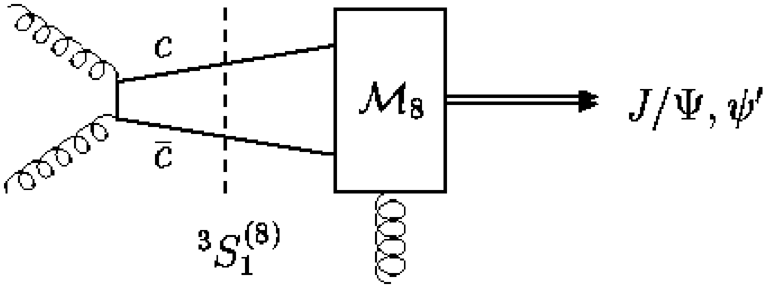
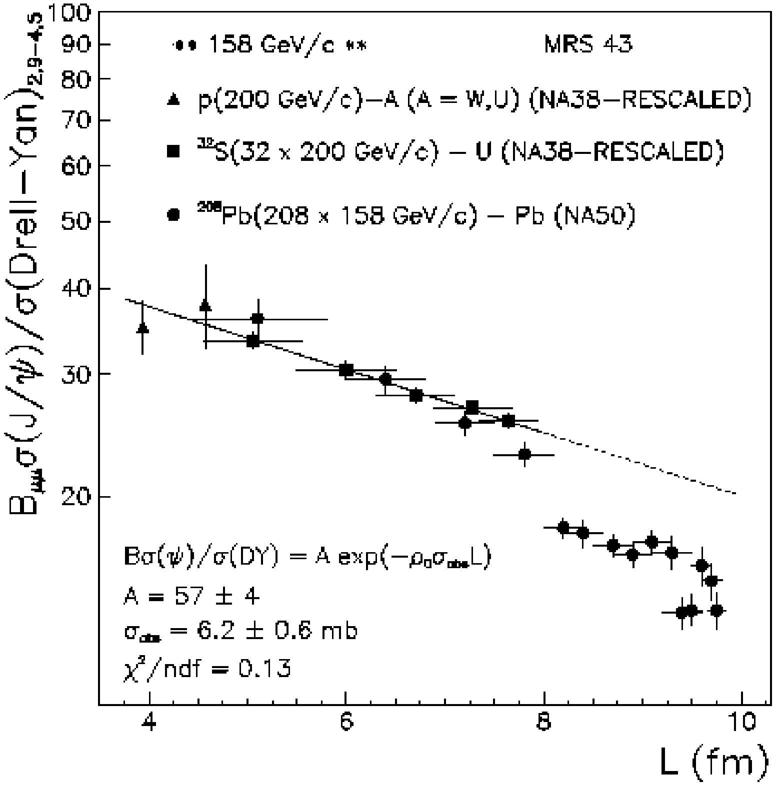


Figure from B. Muller

“Anomalous” J/Ψ Suppression

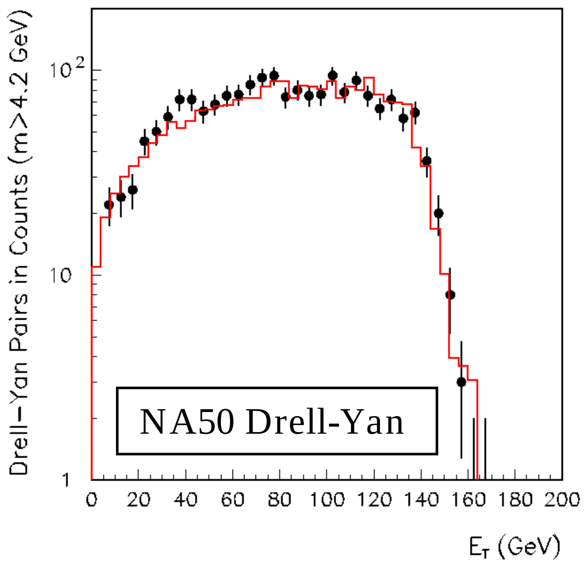
NA38, NA50 J/Ψ to DY ratio

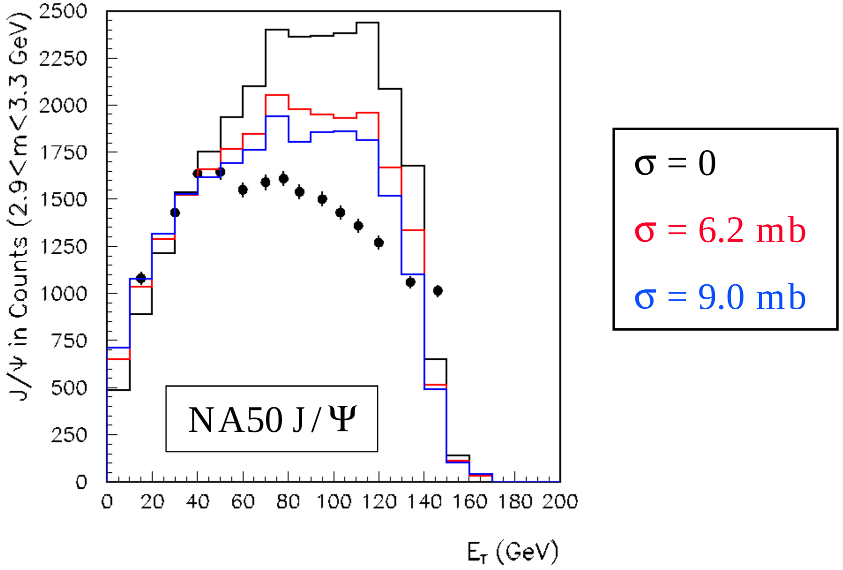


L. Ramello, Quark Matter ‘97

- Yields from p-A and A-A (through S) described by absorption cross section of 6-8 mb--consistent with predictions for c-cbar-g color octet state
- Yields from Pb-Pb collisions display absorption beyond this level, so-called “anomalous suppression”
- Plotted against “L”, the mean length through nuclear material. This is not an ideal parameter--not a measured quantity, saturation for large systems
- Need to look at J/Ψ, DY individually, as a function of centrality

Comparison to Simple Glauber





- Simple Glauber model, with production from all N-N collisions equally likely
  MJB, J.L. Nagle, Physics Letters B465, 21 (1999)
- Collision dynamics based on observed A-A systematics:
  E_T = constant * Wounded nucleons, smeared by 94% /√E resolution
- Drell-Yan yields are fit very well
- J/Ψ yields are not fit well with absorption cross sections from 6-9 mb

“Explaining” Anomalous Suppression

- Absorption by Hadronic Co-Movers

  Inelastic scattering by hadrons at similar momentum

- Gluon Shadowing

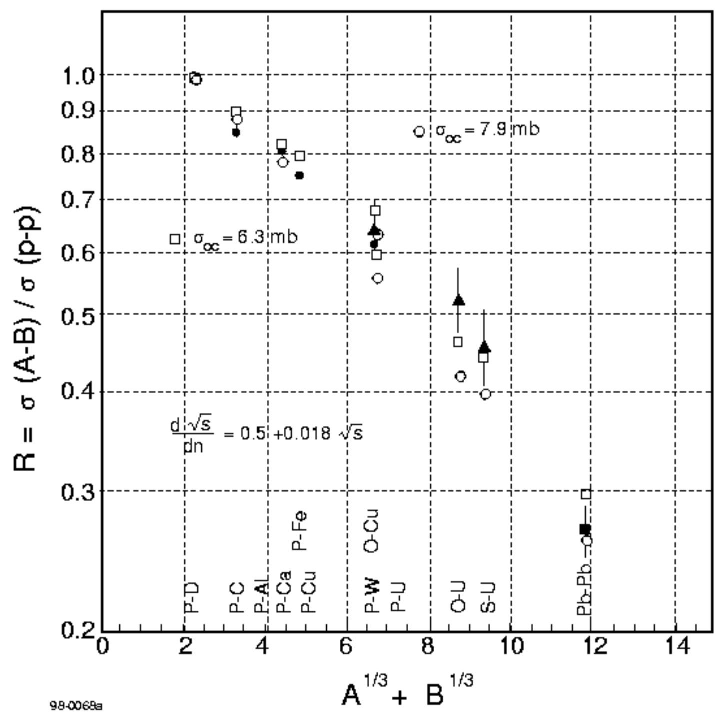
  Quark and Gluon distributions in Nuclei not the same as bare nucleons

- Initial State Energy Loss

  Reduced Production in Later Collisions

- Quark-Gluon Plasma

Energy Loss in Min Bias Collisions

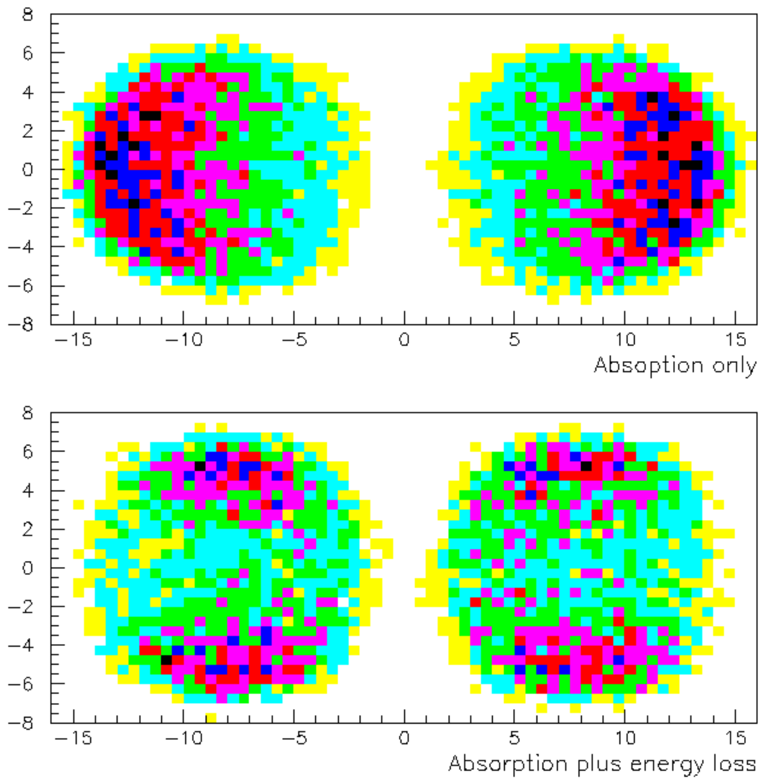


Frankel & Frati, hep-ph/9710532

- J/Ψ yield per N-N Collision, plotted against Mean Number of N-N Collisions
- Absorption only gives simple exponential
- Energy loss suppresses from simple exponential
- Want to look at detailed centrality dependence, for both J/Ψ and Drell-Yan

Geometry of Energy Loss

Absorption only

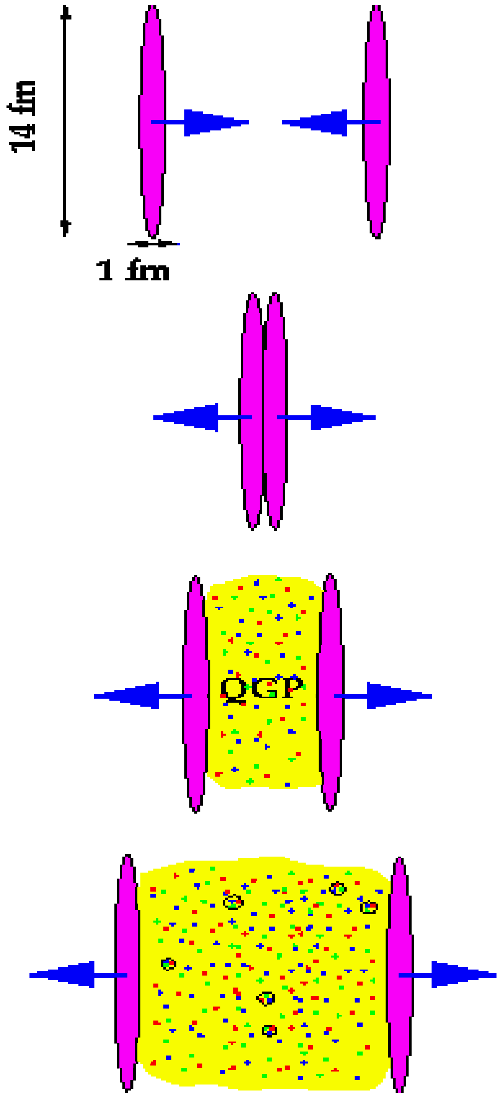


Absorption + Energy Loss

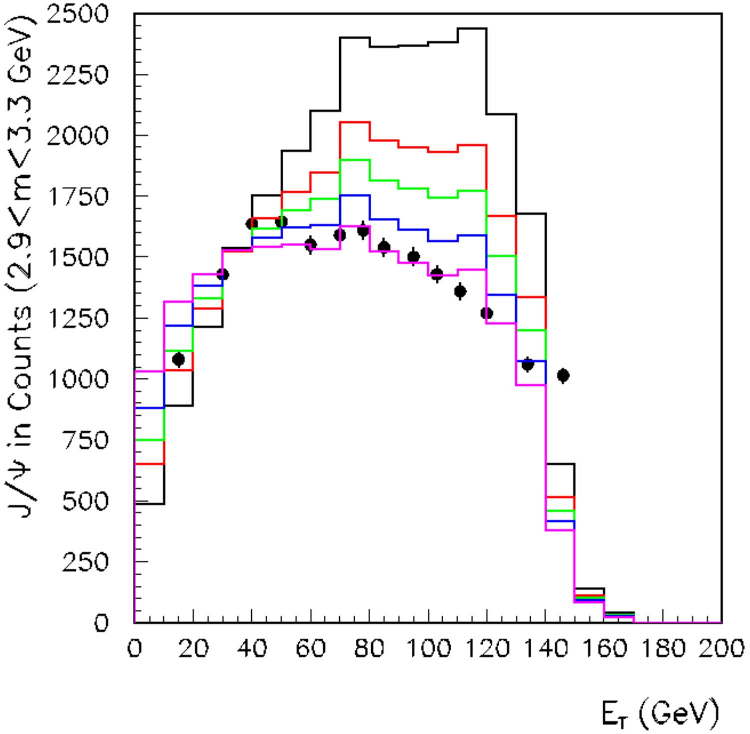
- Nucleons lose energy as they traverse the colliding nucleus
- Production of J/Ψ and Drell-Yan have steep energy dependence
- Affects J/Ψ and DY differently
- Reduces total yield
- Reduces Cronin effect, changes p_t spectrum
- Mimics QGP signal

Time Scales and Collision Dynamics

- Time scale for J/Ψ formation is set by uncertainty relation to be ~0.1 fm/c
- Measurements indicate nucleons lose ~40% of their momentum in each interaction with another nucleon
- Most energy loss is via soft interactions, with a time scale of a few fm/c
- Some fraction of this energy loss is at short time scale, treat as a variable parameter

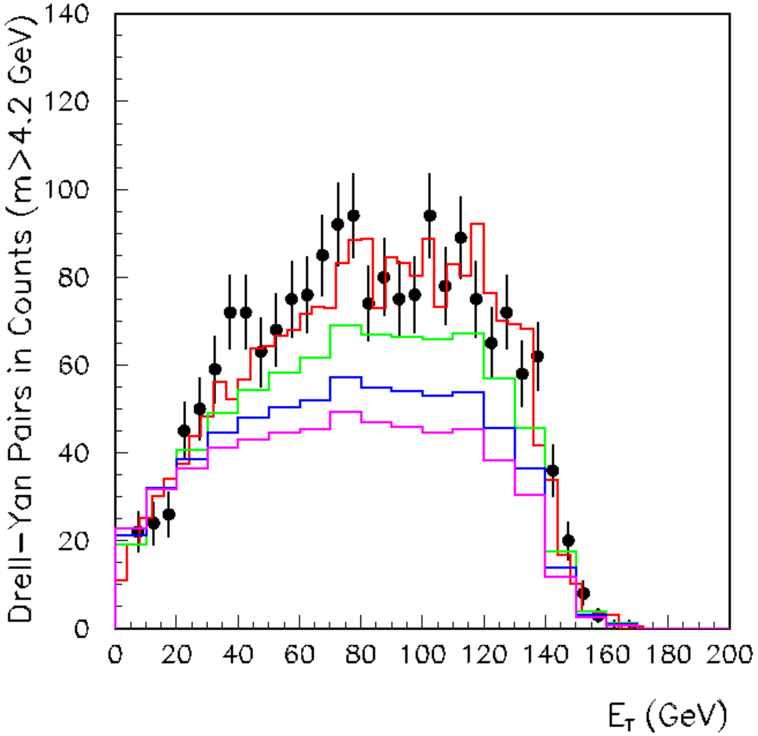


J/Ψ Yields with Energy Loss



- Several values of Energy Loss 0%, 5%, 10% and 15% momentum per collision (0%, 15%, 30%, 50% of total t=∞ loss)
- Normalization chosen to give best fit in lowest two E_T bins
- Highest Energy Loss matches spectral shape well

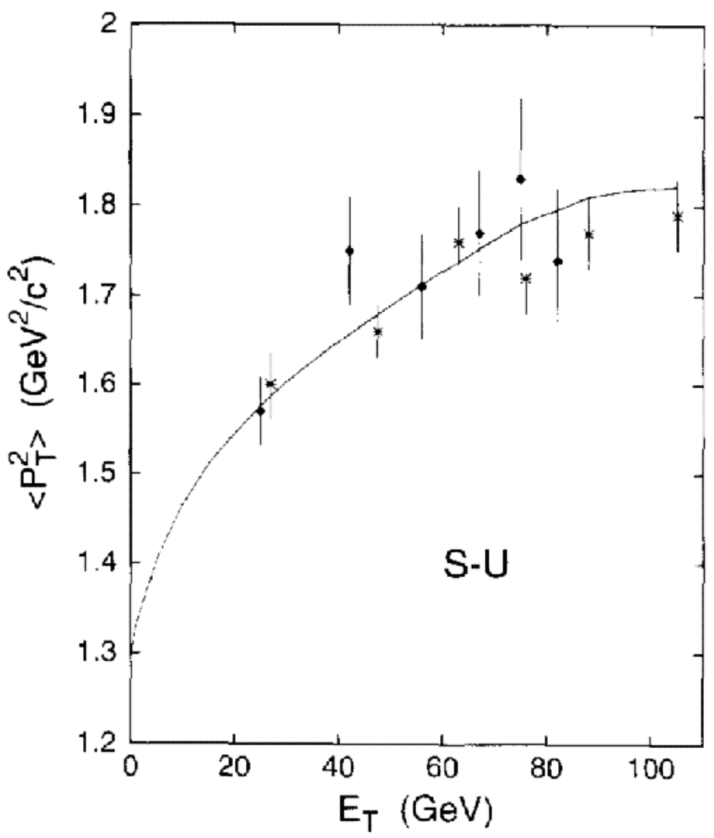
Drell-Yan Yields with Energy Loss



- Several values of Energy Loss 0%, 5%, 10% and 15% momentum per collision
- Normalization chosen to give best fit in lowest E_T bins
- Hard to reconcile any energy loss with data
- Is it reasonable to assume same energy loss is applicable for both J/Ψ and DY?

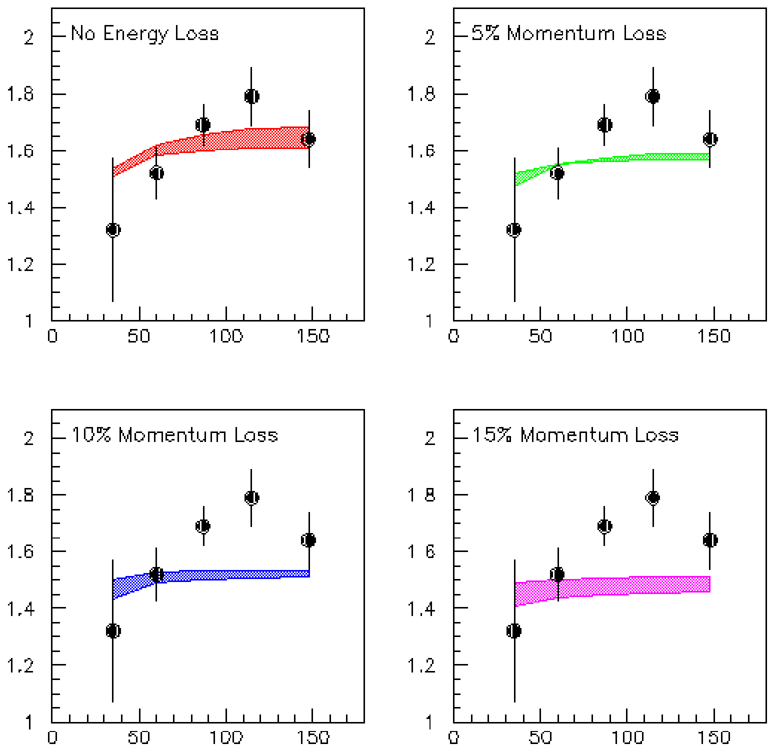
Cronin Effect

$$\langle p_t^2\rangle_N = \langle p_t^2\rangle_{pp} + N\ \Delta p_t^2$$



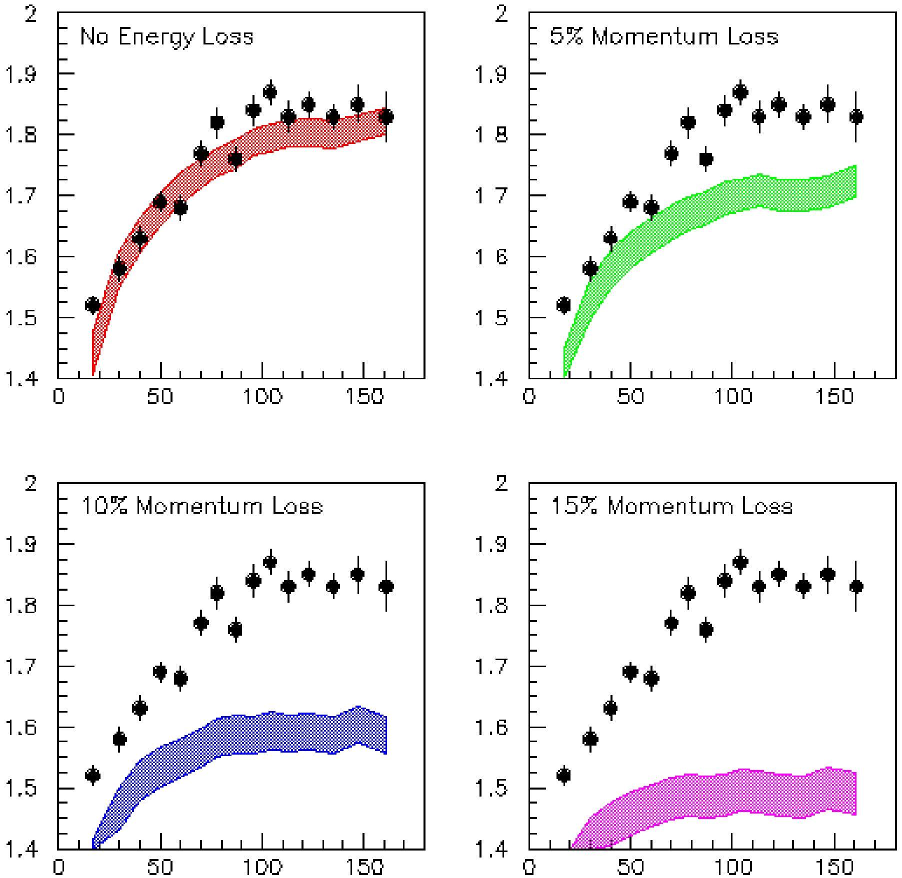
- Prior N-N Collisions broaden transverse momentum ("Cronin effect")
- J/Ψ: $\langle p_t^2\rangle_{pp}$ = 1.23 ± 0.05 GeV^2 (NA3);
  Δp_t^2=0.125 GeV^2 (fit to pA + AA, Kharzeev et al, PLB 405, 14 (1997))
- DY: $\langle p_t^2\rangle_{pp}$ = 1.38 ± 0.07 GeV^2 (NA3);
  Δp_t^2=0.056 GeV^2 (fit to pA + AA, Gavin and Gyulassy, PLB 214, 241 (1988))

Drell-Yan $<p_t^2>$ with Energy Loss



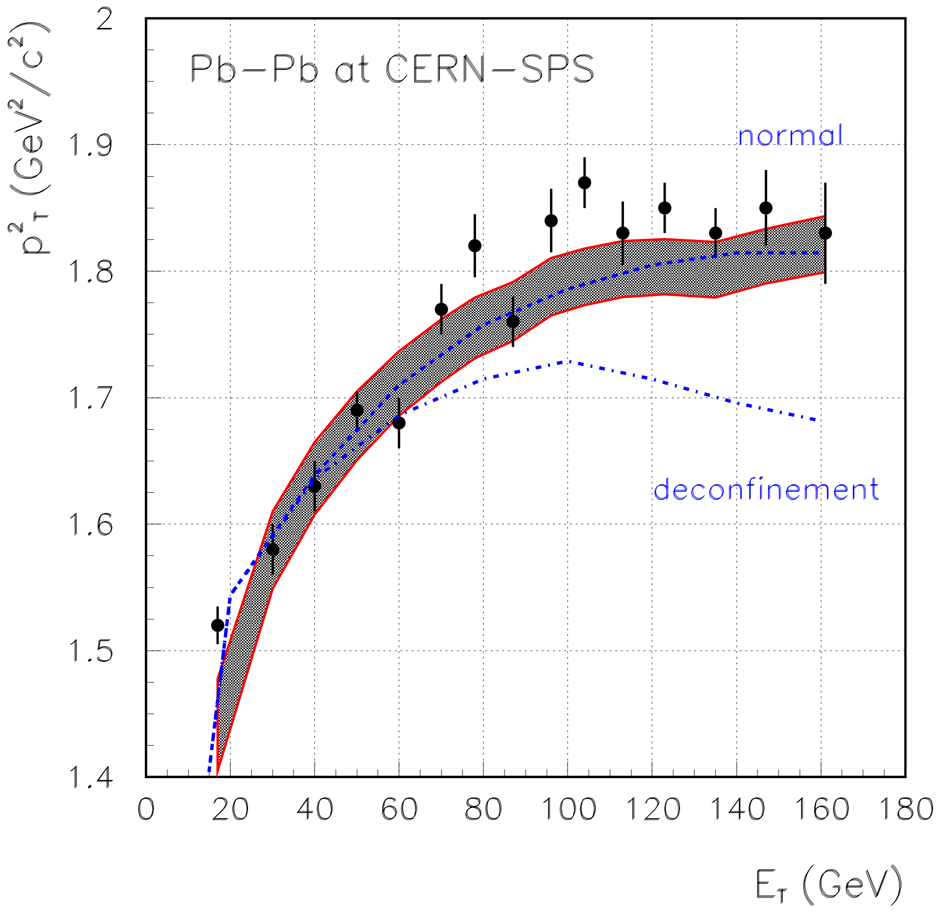
- Several values of Energy Loss 0%, 5%, 10% and 15% momentum per collision
- Spectra not very sensitive to energy loss

J/Ψ $\langle p_t^2 \rangle$ with Energy Loss



- Several values of Energy Loss 0%, 5%, 10% and 15% momentum per collision
- Large values of Energy Loss do not fit data
- Not consistent with Energy Loss required to fit J/Ψ yields

Is QGP necessary to fit J/Ψ $<p_t^2>$?



- Must take error in pp data into account
- pp data taken at 200 GeV; scaling to 158 GeV (linear in s) reduces pp "intercept" to 1.13 GeV^2--changes normalization, not shape
- J.L.Nagle, MJB, Phys. Lett. B465, 21 (1999)
- D.Kharzeev, M.Nardi, H.Satz, Phys. Lett. B405, 14 (1997). Concluded QGP necessary to fit data, but shown here rescaled for pp energy.

Conclusions (Part 1)

- Within normalization uncertainty, J/Ψ $\langle p_t^2 \rangle$ spectrum is consistent with a normal hadronic scenario
- J/ Ψ Yields are not consistent with a simple Glauber calculation. Adding Energy Loss can fit the J/Ψ yield shape ...BUT
- Energy Loss cannot consistently fit both J/Ψ and Drell-Yan yields
- Energy Loss cannot consistently fit both J/Ψ yields and J/Ψ $\langle p_t^2 \rangle$ spectra
- Energy Loss does not appear to explain "anomalous" J/Ψ suppression
- Work ongoing to understand effects of quark and gluon distributions regarding CERN data

Requirements for Analysis

- J/Ψ Measurement

  Yields and Transverse Momenta Spectra

  Both over a large range of system size, from pp, pA, several AA

- Benchmark measurement

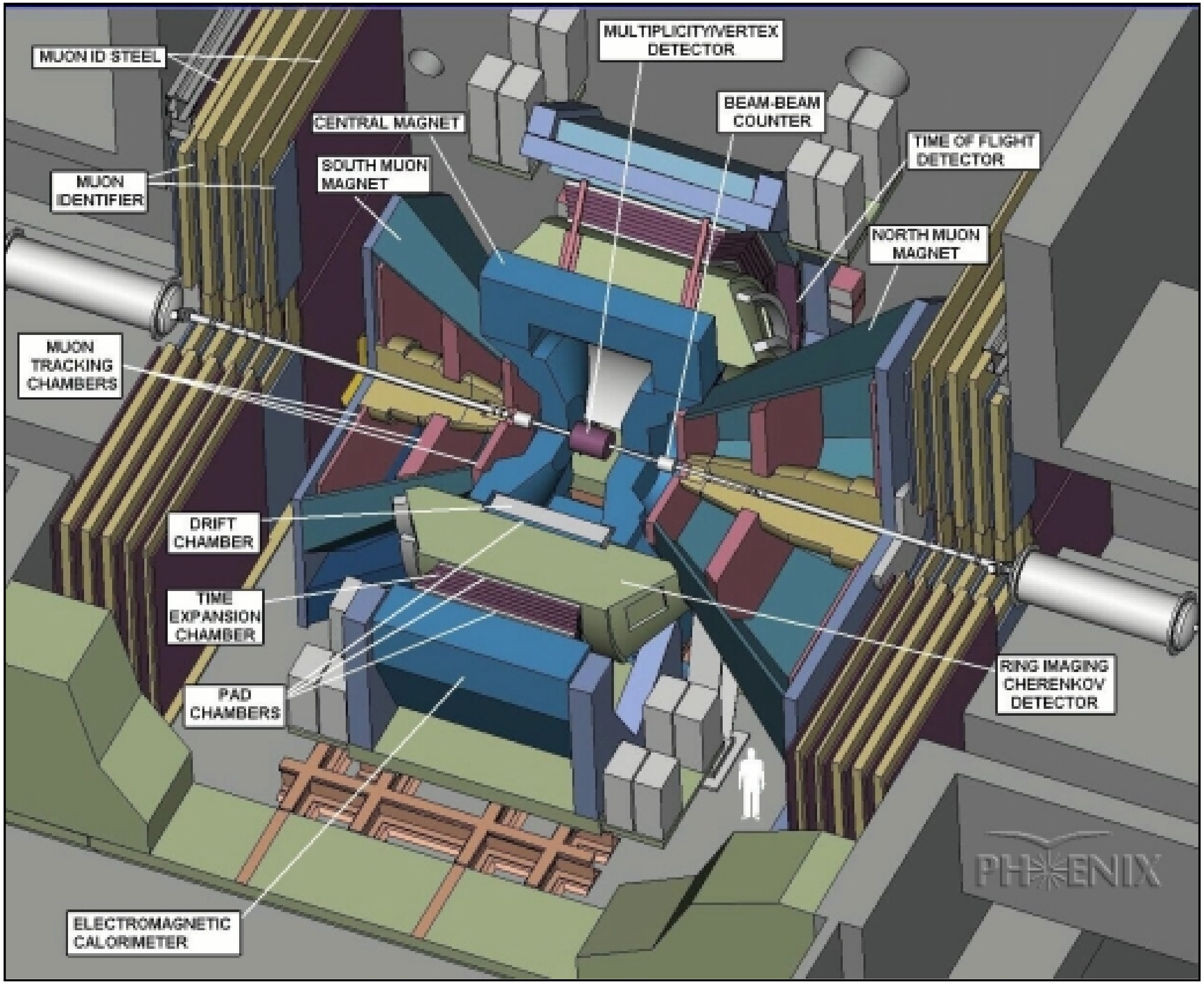
  Drell-Yan over same range of geometries

- Collision Dynamics

  Energy loss systematics from pA, AA

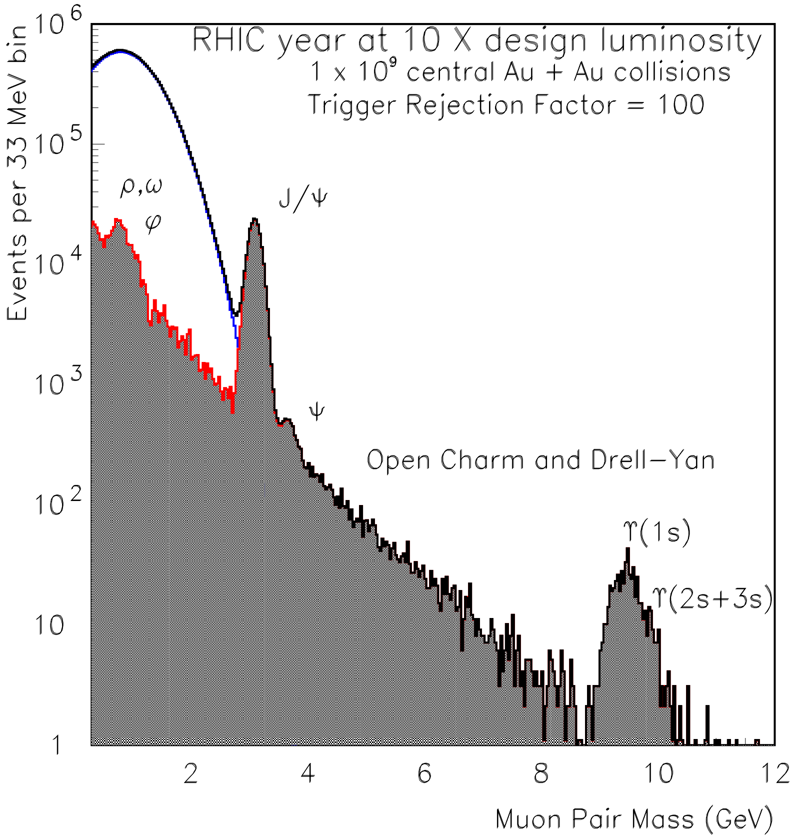
  Geometric dependence of E_t, secondary multiplicity

PHENIX Experiment at RHIC

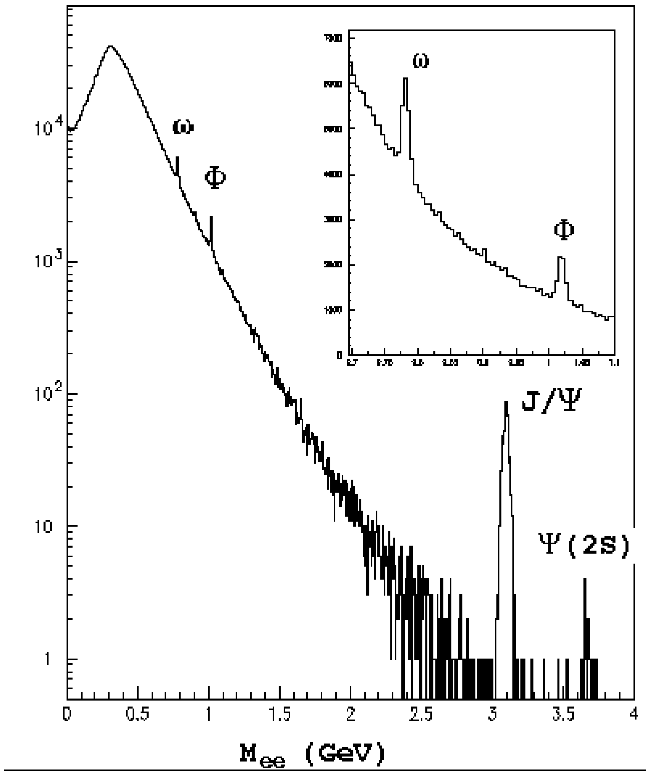


Dileptons in PHENIX

Dimuon spectrum

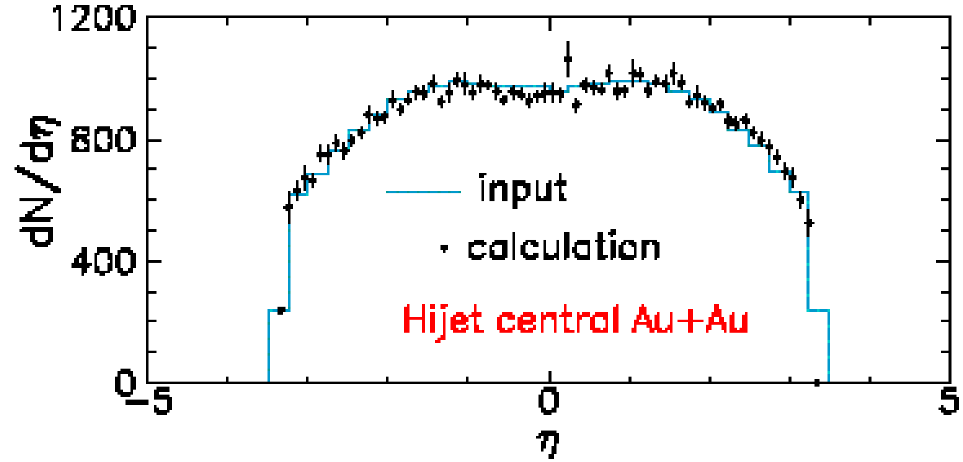


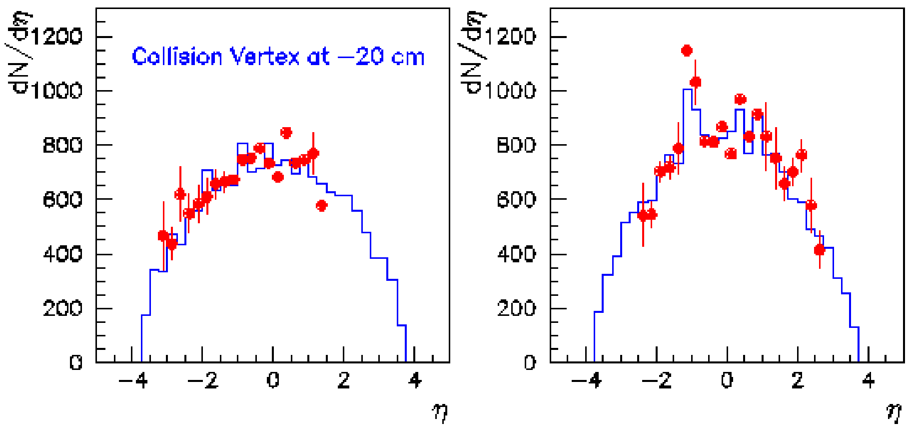
Dielectron Spectrum



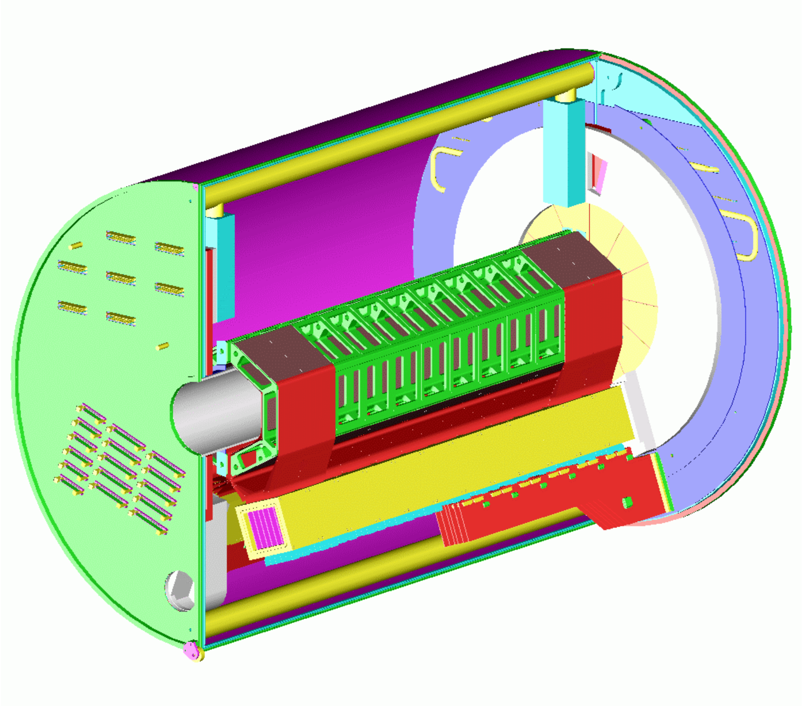
Multiplicity in PHENIX

- Measure Charged Particle Multiplicity accurately over large pseudorapidity range
- Measure dN / dη, dN / dηdϕ
- Sensitive to localized fluctuations on an event-by-event basis



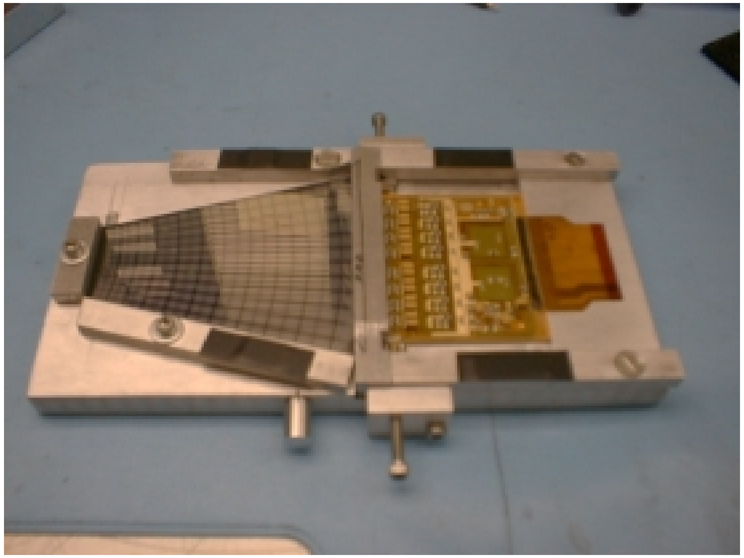


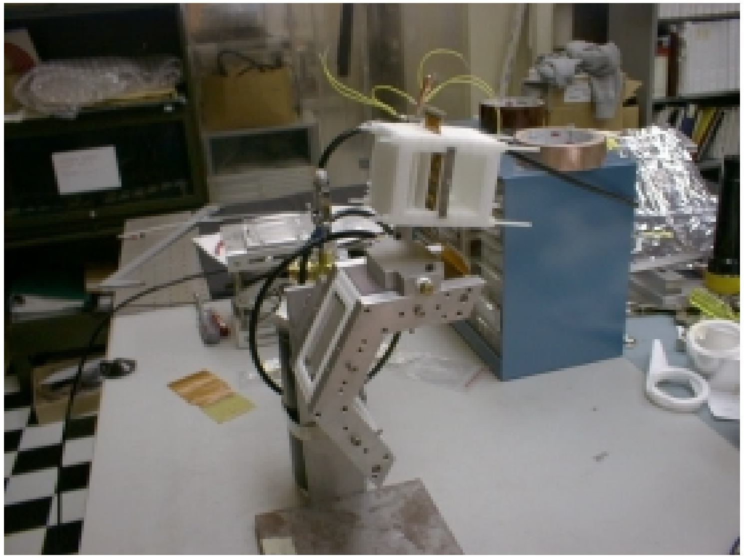
PHENIX MVD

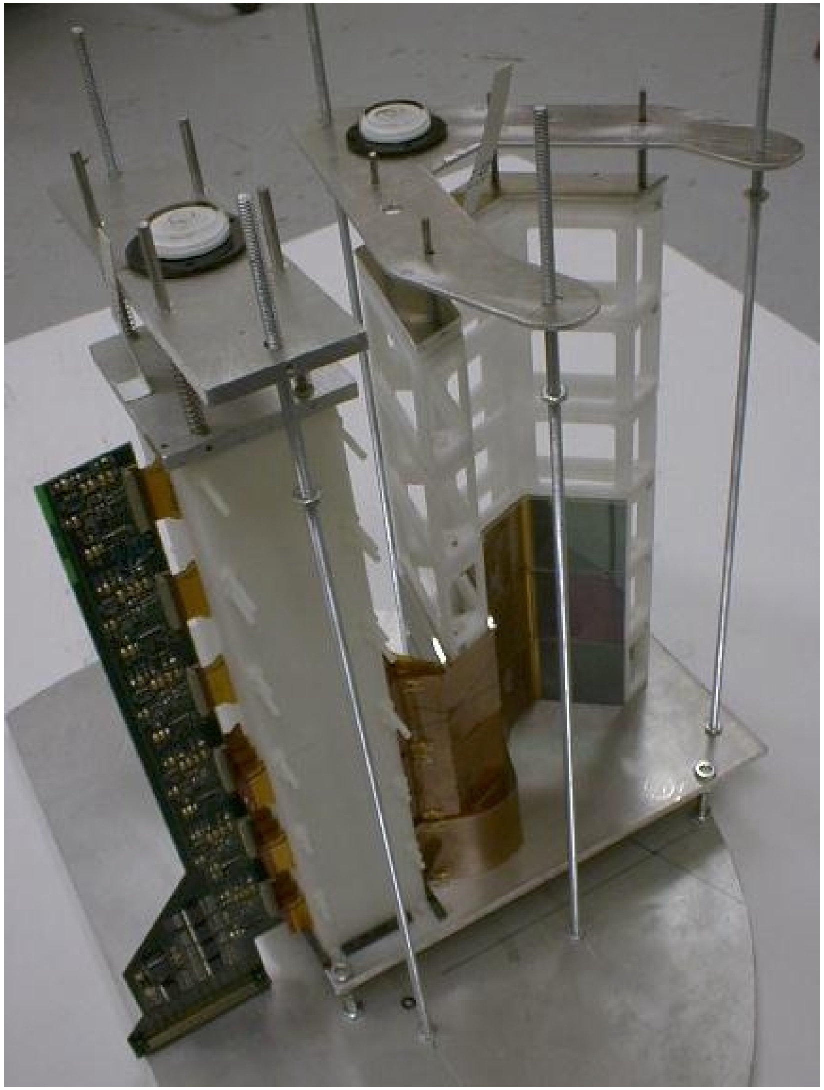


- Inner and Outer Hexagonal Barrels of 200 micron pitch Si Microstrips
- Si Pad Endcaps $2mm^2$ to $4.5mm^2$
- Multichip Module Electronics, 256 Channels in $\sim 4.5cm^2$
- ~35,000 Total Channels

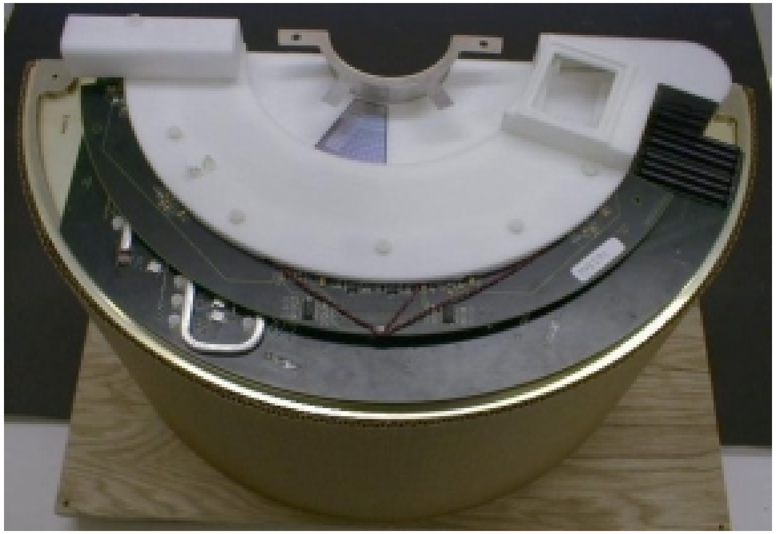
MVD Construction

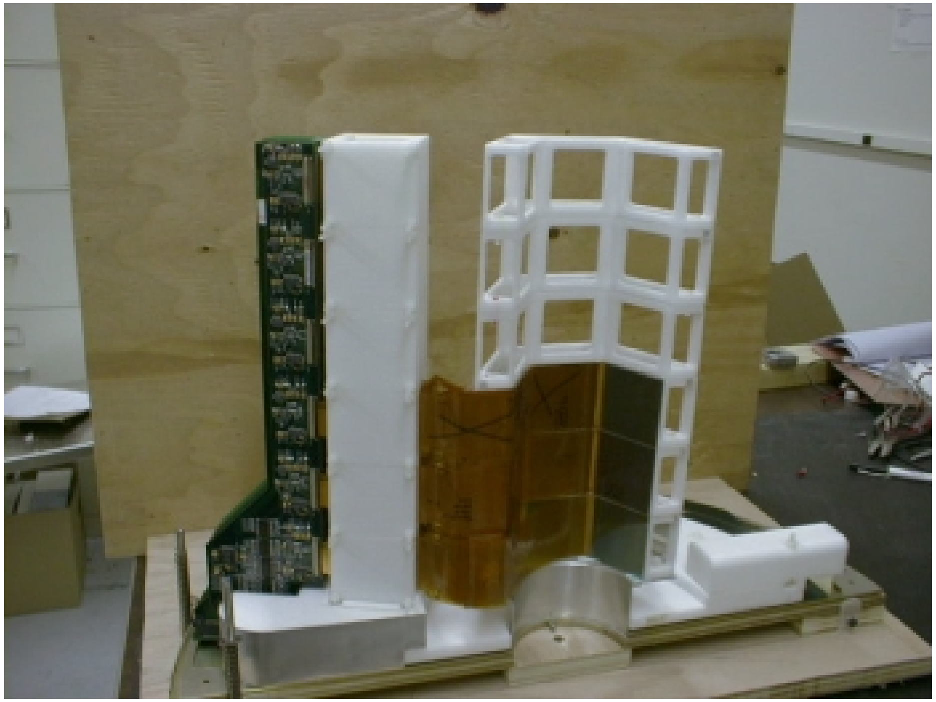






MVD Construction (II)





Conclusions (Part 2)

- We believe we can study the Nuclear Phase Transition to a Quark-Gluon Plasma using Relativistic Heavy Ion collisions.
- The yield of particles containing charm quarks is a fertile area to probe the QGP
- A full understanding of J/Ψ suppression will require systematic measurement of yields over numerous geometries AND an understanding of the collision dynamics
- PHENIX is well situated to make these measurements
- Expect collision dynamics to be the most interesting physics early in the RHIC program, which will set the context for later physics analyses